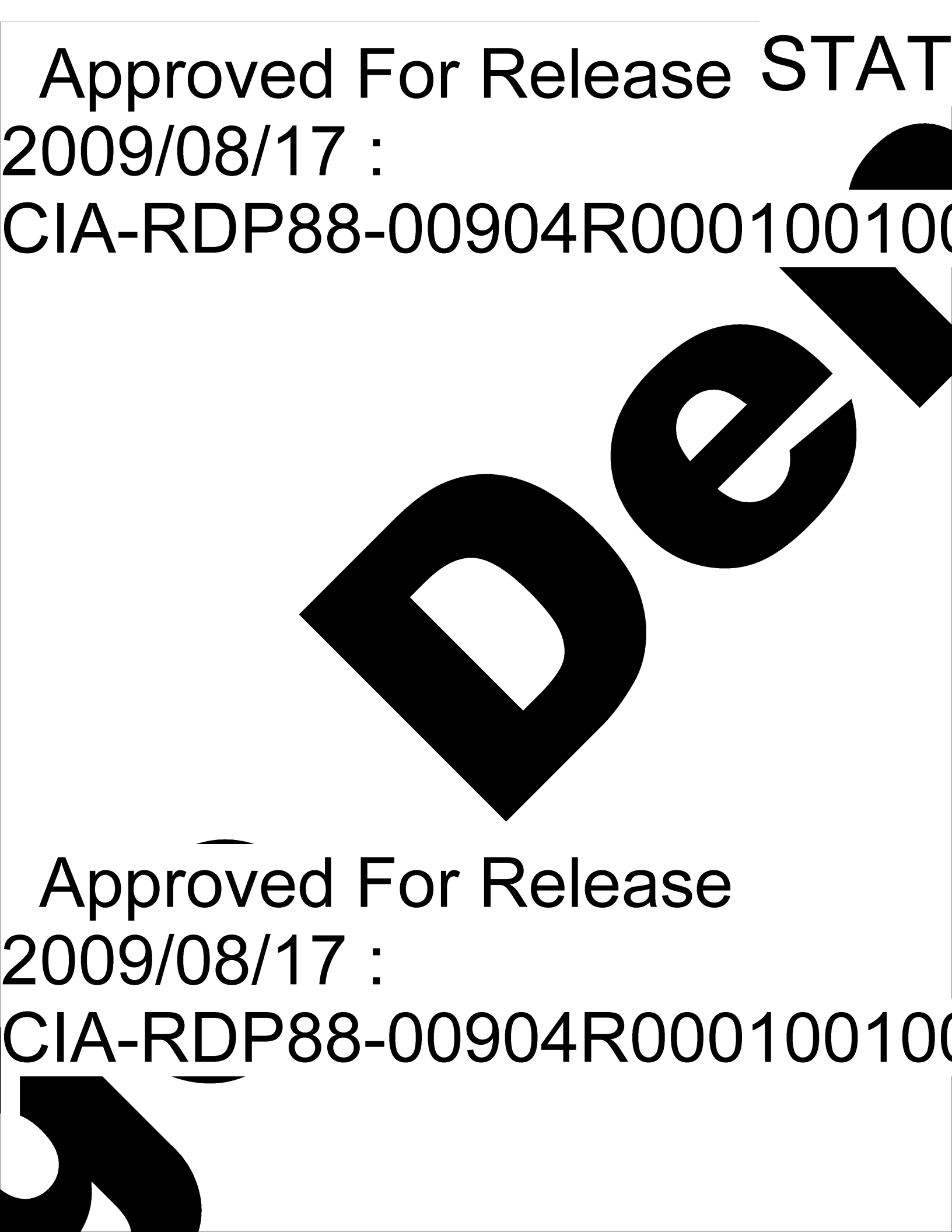

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BEHAVIOUR OF NUCLEAR FUEL UNDER IRRADIATION
(Investigation of Thin Layers of Irradiated Uranium Dioxide)

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Uranium dioxide is at present a nuclear fuel widely used. Under irradiation in a reactor the structure of uranium dioxide changes considerably. Recently a number of investigations of irradiated uranium dioxide have been carried out /1,2,3,4/. However investigations by means of an electron microscope are comparatively scanty. Such important problems as nature of irradiation induced defects, dependence of concentration of defects upon irradiation dose, annealing of defects after irradiation, sites of generation of fission product gas agglomerations and etc. have been not yet found out. This is because the investigation of irradiated uranium dioxide structure by the replica method /3/ cannot solve most problems, while the examination using the transmission electronic microscope is connected with the difficulty of obtaining thin layers of massive material up to about 1000 Å allowing transmission microscopical study. The experimental difficulties were overcome in this work by the following manner. Uranium fine-grained film specimens approximately 500 Å thick were prepared by cathode sputtering 5. Such specimens were "non-transparent" in the electron microscope. The specimens were oxidized to UO_2 due to slow heating in a vacuum furnace and recrystallized, the grain size made to be about 0.25 μ. In this state the specimens were well transparent in the electron microscope. Compared with thinned specimens, these film ones have the following advantages:

1) optimum thickness readily adjustable that allows examination in the transmission electron microscope with high resolution and, hence provides more information;

2) useful area for examination is considerably larger;

3) grain size adjustable within wide limits up to obtaining monocrystalline film specimens;

4) possibility of quantitative investigations, the specimen thickness always being known. The disadvantage of film specimens is some possible difference in structure by comparison with material of massive ones.

The cathode sputtering method /5,6/ was used to prepare metal film specimens of uranium metal containing different per cent of ^{235}U (0.11,0.7 and 90%). After sputtering the thickness, alphaactivity and electrical resistance of specimens were measured by microinterference microscope, type МИИ-4, scintillation counter and ohmmeter, type M8, respectively. Alpha-activity data were used to determine material weight. Material density was calculated from both thickness and weight data. Specific electrical resistance was calculated using electrical resistance and thickness data. Then the film uranium specimens backed on tantalum diaphragms of ⌀ 2 mm with openings of ⌀ 0.2 mm were made to oxidize slowly and were annealed in the vacuum furnace at maximum temperature 1500°C and pressure about 5.10^{-5} mm of mercury. After annealing the thickness and alpha-activity of specimens were measured, material density calculated and preliminary both electron microscope examination and electron diffraction study performed. The structure was examined by the electron microscope, type УЭМБ-100, with resolution improved up to 5 Å. In the electron diffraction study the electron microscope was used as an electron diffraction camera. In order to improve the accuracy when evaluating a lattice spacing the simultaneous survey of both the specimen and the standard was used. All investigations were carried out at the accelerating voltages 100 and 110 kV. The size of uranium dioxide grain and

the density of dislocations were obtained as an average values from five electron photomicrographs. Prepared uranium dioxide specimens on tantalum diaphragms were placed in aluminium cassettes and sealed in argon-filled quartz ampoules. Irradiation was performed during 0.5,5,50 and 500 min in the core of the reactor IPT-1000 in a thermal neutron flux $2.5.10^{13}$ n/cm^2 sec at a channel wall temperature 40°C. A burn-up was calculated. After two day storing the irradiated specimens were examined in the electron microscope. Then the irradiated uranium dioxide specimens were annealed isohronally for 10 min through each 100° in the temperature range 400-1700°C in vacuo about 5.10^{-5} mm of mercury. The annealing temperature was measured by a thermocouple or a pyrometer. After each annealing the specimens were examined in the electron microscope.

Results

A batch of film specimens 480 Å thick was prepared from uranium (90% of ^{235}U). The sputtered layer was white mirror-like with high light reflection coefficient. Layer material density and specific electrical resistance were 14.8 g/cm^3 and about 90.10^{-6} ohm.cm, respectively. Such "thick" specimens were absolutely non-transparent in the electron microscope even at the accelerating voltage 110 kV. In order to define material stucture in the sputtered layer it was required to prepare the thinner uranium specimens. Fig.1a shows such a sputtered uranium specimen about. 50 Å thick. It is seen that the layer consists of small polyhedral grains about 50 Å in size. The electron diffraction pattern of this layer is shown in Fig.1b. Diffraction peaks are broadened that indicates the dispersion nature of the layer. According to the electron diffraction pattern the phase composition of the layer approximates UO_2 but this does not mean that such a composition is formed at sputtering. Thin uranium layers after withdrawing from the cathode sputtering assembly oxidize very rapidly in contact with air. Thick uranium layers (about 500 Å) are more oxidation resistant in air. A specimen of uranium dioxide (90% of ^{235}U) obtained by slow oxidation and annealing

of a sputtered uranium layer in vacuo at the temperature 1500°C is shown in Fig.1c. The layer thickness before annealing was 480 Å and after annealing 700 Å . It is evident that this film specimen consists of "large" polyhedral grains of average size about 0.25 μ . Individual grains have in their centres stacking faults in the form of hexagon of 50 to 150 Å size. Density of dislocations is about 10^9 cm^{-2}. The annealing temperature rise up to 1600°C film specimens were damaged in results of intense collective recrystallization. The electron diffraction pattern of this specimen at the accelerating voltage of 100 kV is shown in Fig.2a. Sharp diffraction peaks verify the absence of stress in the annealed specimen. The data of measurement of interplaner distances on the electron diffraction pattern and X-ray data for those in UO_2 /7/ are given in Table I. It is seen here that the phase composition of the annealed uranium specimen is almost in precise agreement with the stoichiometric one for UO_2. The electron diffraction pattern has no any "useless" line that varifies the absence of impurities. After annealing the colour of the sputtered uranium changed considerably: specimens became transparent with light yellow colouration. Past-annealing material density was 10.8 g/cm^3 and specific electrical resistance rised 10^6 times as much (from about 90.10^{-6} up to higher than 100 ohm.cm).

Specimens of uranium dioxide (90% of ^{235}U) after various annealing periods are shown in Fig.3 (data on itegrated neutron fluxes, burn-up and etc. are given in Table III). A specimen after irradiation to 10^6 fission /cm^3(f/cm^3) is shown in Fig.3a . It is seen that fission fragment tracks are not traced, while on photomicrographs some dislocation loops appear after irradiation. Dislocation loops are located in the main randomly on the whole area of the specimen. Dislocation density is 10^{10} cm^{-2}. A specimen after irradiation to 10^{17} f/cm^3 is shown in Fig.3b. A great number of dislocation loops is seen. Loop diameter varies in wide limits from 20 to 300 Å and dislocation density is 10^{11} cm^{-2}. The electron diffraction

pattern of this specimen is shown in Fig.2b. The following changes are observed:

1)all diffraction peaks broadened, while their relative intensities decreased;

2) diffuse background increased;

3) relative intensities of some diffraction peaks redistributed: lines (111), (200),(400) are decreased but line (220) is increased. In Fig.3c a specimen after irradiation to 10^{18} f/cm^3 is shown. Dislocation density increases by about one order of magnitude in comparison with the previous irradiation period. A great number of pours of about 20 Å form along the boundaries of grains , thesw pours being located mainly on grain surfaces along their boundaries. The electron diffraction pattern of this specimen (Fig.2c) shows that changes observed in the previous specimen (Fig.2b) are even more pronounced here. Fig.3d illustrates a specimen after irradiation to 10^{19} f/cm^3. It is seen that the dislocation density in this specimen is even higher than in the previous one. Dislocation are so numerous that the specimen is almost non-transparent in the electron microscope at the accelerating voltage 100 kV. This electron photomicrograph was taken at the accelerating voltage 110 kV. All previous specimens (Fig.3a, 3b and 3c) withstood the irradiation successfully and were not broken on the diaphragms on which they were backed. After irradiation to 10^{19} f/cm^3 all specimens were broken with only small fragments of these retained on the diaphragms.

The experiment of detection of fission fragments induced in specimens by irradiation was carried out. For this purpose two-layer fine-grained objects of W-UO_2(90% of ^{235}U) 50-6 Å thick with high efficiency for fission fragment detection were prepared. Such two-layer specimen after irradiation to 10^{18} f/cm^3 is shown in Fig.4. The whole specimen area has tracks due fission fragments. It is seen that fission fragments scattered both at small angles to the object plane and perpendicularly are detected.

In order to find out the manner of fission rate influence on uranium dioxide structure at the same burn-up the dioxide

specimens prepared from natural uranium (0.7% of ^{235}U) were irradiated. In Fig.5 a specimen about 600 Å thick after irradiation to 9.10^{16} f/cm^3 is shown. It is evident that dislocation density in this specimen is near the same as in the uranium dioxide one (Fig.3b), i.e. about 10^{11} cm^{-2}. The shape and dimensions of dislocation loops are the same.

In order to find out the nature of dislocation loops the same areas of a uranium dioxide specimen were subjected before and after irradiation to the sighting examination by the electron microscope. Dioxide specimens were produced from uranium depleted according to the nuclide ^{235}U up to 0.11% with the object to obtain the lower density of defects. Specimens were photographed in the electron microscope and irradiated in the reactor up to $1.4.10^{16}$ f/cm^3. Then the same areas of uranium dioxide were examined in the electron microscope after irradiation. In Fig.6 the same area of the uranium dioxide specimen about 700 Å thick (0.11% of ^{235}U) before and after irradiation is shown. Fission fragments tracks are not traced here as in Fig.3a . It is evident that at the initial stage of irradiation the dislocation loops begin to form within grains around various "obstacles" (areas A and A', Б and Б' and others around stacking faults, Fig.6).

Kinetics of annealing of irradiated uranium dioxide spesimen (Fig.3c) vs temperature was studied. The specimen structure practically suffered no changes after isochronal annealing for 10 min through each 100°C in the temperature range 400-800°C in vacuo. This specimen after 10 min annealing in vacuo at the temperature 900°C is shown in Fig.7a. It is seen here some decrease of the dislocation density. A great number of very small "light defects" about 10 Å in size appear uniformly in the whole volume of the specimen. The contrast of "light defects" does not depend on the crystallographic orientation of grains. The same specimen after additional annealing in vacuo for 10 min at 1000°C is shown in Fig.7b . It is seen that in results of annealing "small" loops transforms into "large" ones each of the latters constisting of a pair of edge dislocations of opposite signs. The dislocation loop concentration is decreasing appreciably. The electron diffraction pat-

tern of this specimen is shown in Fig.2d. It is seen, that after annealing the diffraction peaks narrow, diffusion background diminishes and relative intensities of diffraction peaks become to return to initial shape. The specimen in Fig.7c is the same as in Fig.7b but after additional annealing for 10 min at 1100°C. It is evident that at this temperature practically all dislocation loops within grains are annealed and the original polyhedral structure inherent to the grain before the irradiation is restored. The pours along grain boundaries "cure" and in addition the pilings up of dark sports about 50 Å in size form. After annealing of dislocations the "light defects" about 10 Å in size do not change and remain across the whole specimen volume. "Light defect" concentration is very high, e.i. about 10^{18} cm^{-3}. After slight refocusing of the electron microscope objective the contrast of "light defects" reverses: light points at grey background become darker than the background. From the image formation mechanism in the electron microscope follows that these "light defects" are pours but no inclusions. Fig.7d shows tha same specimen as in Fig.7c but after additional annealings for 10 min at temperatures 1200, 1300, 1400 and 1500°C. It is obvious that "light defects" migrate and form larger defects up to 100 Å in size. The piling up along grain boundaries migrate simultaneously and give rise to stacking faults in the form of hexagon up to 300 Å in size. The electron diffraction pattern of this specimen (Fig.2e) is in accordance with the electron diffraction pattern of the unirradiated one (Fig.2a).

Should be noted, that intense collective recrystallization in irradiated uranium dioxide specimens originates only at 1800°C while in the unirradiated ones at 1600°C.

Discussion

Results of measurement of density, specific electrical resistance and phase composition, and etc. in sputtered and annealed uranium specimens are given in Table II. By comparing the measured results with the tabulated data one may conclude that at cathode sputtering of uranium a finely dispersated

layer of metallic uranium contaminated with residual gases is formed. At slow heating of this layer in vacuo about 5.10^{-5} mm of mercury the uranium is oxidized to UO_2. Then as the temperature rises up to 1500°C the collective recrystallization of finely dispersated uranium dioxide occures and grain size augments 50 times as much, from about 50 to about 2500 Å (0.25 μ). Some grains approach about 1 μ in size. Adsorbed gases release from the specimen and crystalline imperfections anneal. In results one obtains an uranium dioxide film specimen well annealed of 10.8 g/cm^3 density with regular polyhedral grains and density of dislocations of about 10^9 cm^{-2}. Considerable (from the point of view of electron microscopy) thickness amounting to 700 Å or 74 μ g/cm^2 does not prevent the transmission of this crystalline specimen in the electron microscope and allows to obtain high resolution (reveal of individual elements of the structure up to 10 Å in size). It is evident that these film specimens of uranium dioxide are quite useful for examination of irradiation induced defects in material because dimensions of these defects are much lower than 700 Å and vary in the range from atom dimensions to several hundred angstroms.

Table III summarizes the irradiation data for all film specimens of uranium dioxide. On the base of these results one may conclude the following. At "small" irradiation doses for uranium dioxide (up to about 10^{18} f/cm^3) the density of irradiation-induced dislocations is proportional to the irradiation dose.

It is known that density of dislocations in well annealed metals is about 10^8 cm^{-2}, while in strongly strained ones it is about 10^{12} cm^{-2} /8/. Table III shows that dislocation density in annealed uranium dioxide specimens is about 10^9 cm^{-2} while in the irradiated ones it is higher than 10^{12} cm^{-2}. From this follows that minimum and maximum densities of dislocations found out for uranium dioxide are in approximate agreement with those for metals.

In film uranium dioxide specimens (90% of ^{235}U) the following relation between the concentration of dislocation loops and that of fission fragment tracks is observed:

$$\frac{\text{Dislocation loop quantity in 1 cm}^3 \text{ of } UO_2}{\text{Fission fragment track quantity in 1 cm}^3 \text{ of } UO_2} \cong 0.3$$

This shows that the efficiency of dislocation loop formation caused by fission fragments is very low at an average . It is obvious from comparison of two irradiated specimens shown in Fig.3a and 4. Through 1 cm^2 surface area of a specimen shown in Fig.3a "passes" the same amount of fission fragments as through the 1 cm^2 area of a specimen shown in Fig.4. It is seen, however, that the amount of dislocation loops formed in the specimen in Fig.3a is comparatively low ($2.5 \cdot 10^{10}$ dislocation loop/cm^2 in Fig.3a and $6 \cdot 10^{10}$ track/cm^2 in Fig.4).

Irradiated specimens of uranium dioxide containing 90% of ^{235}U and of uranium dioxide containing 0.7% of ^{235}U shown in Fig.3b and 5, respectively, have near identical burn-up but fission rate in the first specimen due to the high concentration of ^{235}U is 120 times as much as in the second specimen. However, this does not affect the structure of uranium dioxide with 0.7% concentration of ^{235}U: dislocation dimensions and density in irradiated uranium dioxide containing 0.7% of ^{235}U correspond approximately to those in irradiated uranium dioxide with 90% concentration of ^{235}U. For uranium dioxide with 0.7% concentration of ^{235}U the relation.

$$\frac{\text{Dislocation loop quantity in 1 cm}^3 \text{ of } UO_2}{\text{Fission fragment track quantity in 1 cm}^3 \text{ of } UO_2} \cong 0.3$$

corresponds to that for uranium dioxide with 90% concentration of ^{235}U. Hence one may conclude that at a thermal neutron flux of $2.5 \cdot 10^{13}$ n/cm^2sec and at a given irradiation temperature the fission rate does not cause differences in the structure of irradiated specimens. The thermal conductivity conditions in the experiment described are probably those which prodereliable heat conduction from film specimens of uranium dioxide (90% of ^{235}U); in the course of irradiation a temperature probably is not higher than 800°C (the temperature at which dislocation loop annealing starts). In other words, film specimens of uranium dioxide (0.7% of ^{235}U) may be irradiated in a thermal neutron flux $2.5 \cdot 10^{15}$ n/cm^2 sec., the structure after irradiation being the same as after irradiation

of these specimens in the flux $2.5 \cdot 10^{13}$ n/cm^2 sec.

Study of the annealing kinetic of irradiated uranium dioxide specimens (90% of ^{235}U) shows that annealing of defects is realized in two steps: at first at temperature range 800-1100°C dislocation loops migrate and anneal absolutely then in the range from 1200 to 1700°C "light defects" migrate. It is known, for example, that in homeopolar crystals the lowest activation energy of migration pertains to interstitial atoms (about 3/4 eV). Single vacancies have the higher activation energy of migration (about 1 eV). Even higher activation energy of migration is exhibited by double vacancies (about 13/4 eV) /8/ . Therefore, on the basis of annealing data one may suppose that dislocation loops are the pilings up of interstitial atoms, while "light defects" are the pilings up to vacancies. Vacancy nature of "light defects" is verified also by the presence of contrast variation effect at the above mentioned refocusing of an image.

In the previous work /6/ was shown that fission fragments caused serious damages in amorphous film specimens of uranium. Along a fission fragment track in such specimens the hollow channels of ø 40-140 Å were formed, displaced atoms being situated at the ends of these channels. In crystalline uranium dioside the picture should differ from described above: knockedon atoms by means of focused collisions may "pass" large distance from a fission fragment track. These atoms will retain and condense around various "obstacles" within a grain and along its boundary. In such a way the dislocation loops may form. It may be seen clearly in Fig.6b an initial stage of dislocation loop formationa along stacking fault boundaries within a grain. The hollow channels in crastalline uranium dioxide formed along a fission fragments track may be "cured" and vacancies, double vacancies and vacancy complexes may appear in their places. One may suppose that "light defects" of about 10 Å in size and of vacancy nature distributed uniformly across the whole irradiated specimen volume (Fig.7a, 7b, 7c) form in results of spontaneous situations along a fission fragment track.

The most probable places of the gaseous pour generation in uranium dioxide may be "light defects", grain boundaries and particularly common boundaries of adjacent grains. In all irradiated uranium dioxide specimens studied the pours were formed along the grain boundaries only. This may be seen, for example, in Fig.3c, where plurality of small pours may be observed along grain boundaries, while one large pour of about 400 Å is at the joint of four grains. From this follows that grain boundaries are the weakest points in the material. Therefore the discontinuity and damage of irradiated uranium dioxide specimens occure along grain boundaries.

Diffraction peak broadening shown in electron diffraction patterns of Fig.2b and 2c and caused by irradiation dose increase may indicate an arising of stress in the material and crushing of mosaic blocks. The simultaneous electron microscope examination and electron diffraction study of the same specimens give adequate answers. Crushing of grains and subgrains after annealing is not observed from which follows therefore that in uranium dioxide under irradiation arise stresses only. The photomicrographs (Fig.3b, 5 and others) show clearly the microregions in which material is stressed. These regions are around dislocation loops formed by the pilings up of interstitial atoms. Arising and development of stresses in uranium dioxide under irradiation is supported qualitatively by the fact that all uranium dioxide specimens (90% of ^{235}U) destroy after irradiation to 10^{19} f/cm^3. Annealing of irradiated uranium dioxide specimens over temperature range 800-1100°C causes migration of interstitial atoms, removes stresses and narrows diffraction peaks (Fig.2d). Should be noted that at given relatively low burn-ups (0.04 atom per cent of uranium)in uranium dioxide (90% of ^{235}U) it is difficult to measure the change of lattice spacing of UO_2 found at high burn-ups (33 atom per cent of uranium) by other authers /4/ .

Conclusions

1. It is found that irradiation causes in uranium dioxide the defects of two kinds: dislocation loops from 20 to 300 Å in diameter and "light defects" about 10 Å in size.

2. The examination of the same areas by an electron microscope and annealing of defects show that dislocation loops in uranium dioxide grains are formed due to the condensation of interstitial atoms around various "obstacles". The site of dislocation loops is not connected with that of fission fragment tracks. "Light defects" are of vacancy character and their sites depend obviously on the situation of fission fragment traces.

3. It is found that up to burn-ups corresponding to about 10^{18} f/cm^3 the amount of dislocation loops in uranium dioxide under irradiation is proportional to the irradiation dose.

4. The density of dislocations in annealed uranium dioxide specimens is measured. It is about 10^9 cm^{-2}. In uranium dioxide specimens after irradiation to 10^{19} f/cm^3 the density of dislocations exceeds 10^{12} cm^{-2}.

5. It is found that the efficiency of dislocation loop formation in given irradiated specimens of uranium dioxide is comparatively low: about 0.3 dislocation loop at an average for one track of a fission fragment.

6. Fission rate in uranium dioxide at a thermal neutron flux $2.5 \cdot 10^{13}$ n/cm^2.sec and reactor channel temperature 40°C does not influence the final uranium dioxide structure: at the same burn-ups in the natural uranium dioxide and in uranium dioxide containing 90% of ^{235}U the amount, shape and dimensions of dislocation loops are identical.

7. It is found that annealing of past-irradiation defects in uranium dioxide is effected in two steps: in the temperature range 800-1100°C dislocation loops are annealed while at temperatures in the range 1200-1700°C "light defects" migrate.

8. Electron diffraction study shows that irradiation causes in uranium dioxide stresses increasing with the irradiation dose growing. These stresses arise around dislocation loops and anneal gradually at the same time with annealing of dislocation loops.

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Table I

PERIOD AND INTERPLANER DISTANCES FOR URANIUM DIOXIDE SPECIMEN SHOWN IN FIG. 1c

Measured		From Tables [7]	
Uranium dioxide specimen		UO_2	
d_{hkl} [Å]	a [Å]	d_{hkl} [Å]	hkl
3.1514	5.458	3.157	111
2.7294	5.459	2.735	200
1.9293	5.456	1.934	220
1.6460	5.460	1.649	311
1.5762	5.460	1.579	222
1.3649	5.459	1.368	400
1.2528	5.461	1.255	331
1.2210	5.460	1.223	420
1.1149	5.462	1.116	422
1.0513	5.463	1.052	511
0.9633	5.460	0.9666	440
0.9229	5.459	0.924	531
0.9100	5.460	0.911	600
a = 5.461 ± 0.002 Å		a = 5.470 Å	

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Table II

SOME PHYSICAL PROPERTIES OF SPUTTERED URANIUM SPECIMENS

	Specimen	Density g/cm^3	Specific electrical resistance ohm.cm.	Phase composition	Appearance
Measured	Sputtered uranium layer after preparation	14.8	$\sim 90.10^{-6}$	-	White, mirror-like
	Sputtered uranium layer after oxidation and annealing	10.8	>100	UO_2	Transparent with light yellow colouration
From handbook	Metallic uranium	19.04	$32.2 \cdot 10^{-6}$	U	White with light yellow colouration
	Uranium dioxide	10.96	from 10 to $2.5 \cdot 10^7$	UO_2	Brown

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Table III

IRRADIATION DATA FOR FILM URANIUM DIOXIDE SPECIMENS

Fig. No.	Specimen	Measured: Thickness, Å	Measured: Irradiation time, min	Calculated: Volume concentration of dislocation loops, loop/cm³	Calculated: Dislocation density, cm⁻²	Calculated: Thermal neutron flux, n/cm²	Calculated: Fission quantity f/cm³	Calculated: Burn-up at % U	Calculated: Energy release Mwd/tn ^{235}U	Calculated: Fission fragment track density, track/cm²
1c	UO_2(90% of ^{235}U)	700	0	$\sim 3 \cdot 10^{14}$	$\sim 10^{9}$	0	0	0	0	0
3a	UO_2(90% of ^{235}U)	700	0.5	$3.6 \cdot 10^{15}$	10^{10}	$8 \cdot 10^{14}$	10^{16}	$4 \cdot 10^{-5}$	0.35	$7 \cdot 10^{10}$
3b	UO_2(90% of ^{235}U)	700	5	$3.6 \cdot 10^{16}$	10^{11}	$8 \cdot 10^{15}$	10^{17}	$4 \cdot 10^{-4}$	3.5	$7 \cdot 10^{11}$
3c	UO_2 (90% of ^{235}U)	700	50	$\sim 3 \cdot 10^{17}$	$\sim 10^{12}$	$8 \cdot 10^{16}$	10^{18}	$4 \cdot 10^{-3}$	35	$7 \cdot 10^{12}$
3d	UO_2(90% of ^{235}U)	700	500	$> 3 \cdot 10^{17}$	$> 10^{12}$	$8 \cdot 10^{17}$	10^{19}	$4 \cdot 10^{-2}$	350	$7 \cdot 10^{13}$
5	UO_2(0.7% of ^{235}U)	600	650	$\sim 3 \cdot 10^{16}$	$\sim 10^{11}$	10^{18}	$9 \cdot 10^{16}$	$3.6 \cdot 10^{-4}$	400	$5 \cdot 10^{11}$
6	UO_2(0.11% of ^{235}U)	700	650	-	-	10^{18}	$1.4 \cdot 10^{16}$	$5.6 \cdot 10^{-5}$	400	10^{11}
4	W-UO_2(90% of ^{235}U)	50-6	50	-	-	$8 \cdot 10^{16}$	10^{18}	$4 \cdot 10^{-3}$	35	$6 \cdot 10^{10}$

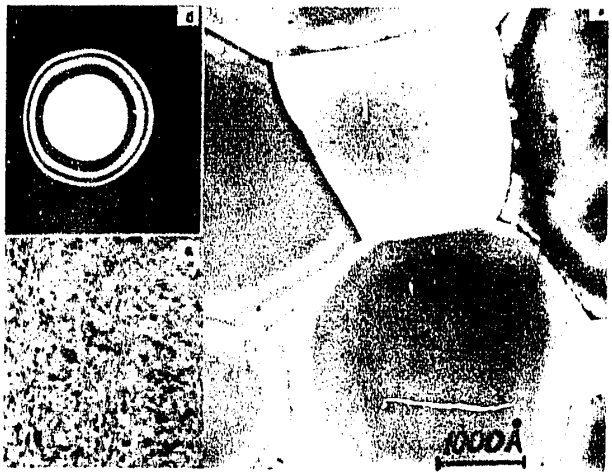

Fig.1. Uranium dioxide (90% of ^{235}U)
a) specimen after sputtering (photomicrograph)
b) specimen after sputtering (electron diffraction pattern)
c) specimen after sputtering and annealing at 1500°C; density of dislocations is about 10^9 cm^{-2}

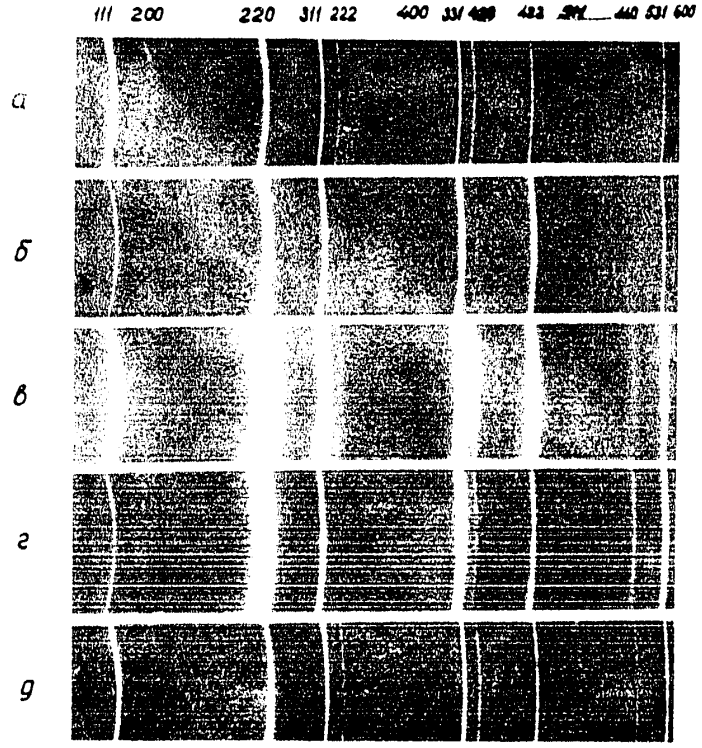

Fig.2. Electron diffraction patterns of uranium dioxide specimens (90% of ^{235}U)
a) specimen before irradiation (Fig.1c)
b) specimen after irradiation to 10^{17} f/cm^3 (Fig.3b)
c) specimen after irradiation to 10^{18} f/m^3 (Fig.3c)
d) irradiated specimen after 10 min annealing at 1000°C (Fig.7b)
e) irradiated specimen after 10 min annealing at 1500°C (Fig. 7d).

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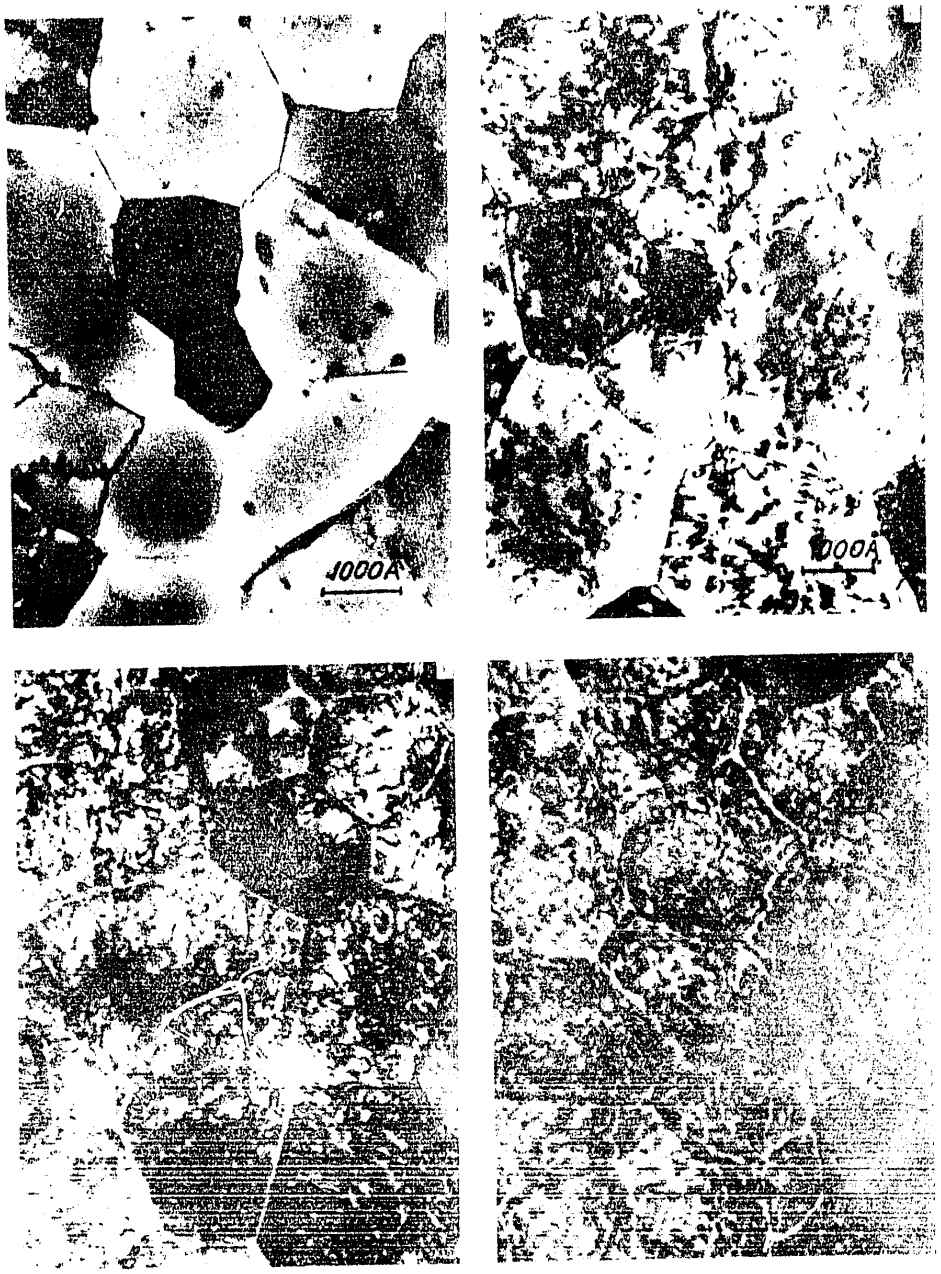

Fig.3. Irradiated uranium dioxide specimens (90% of ^{235}U)
a) 10^{16} f/cm^3; dislocation density 10^{11} cm^{-2}
b) 10^{17} f/cm^3; dislocation density 10^{11} cm^{-2}
c) 10^{18} f/cm^3; dislocation density about 10^{12} cm^{-2};
A - large pour at the boundary of four adjacent grains
d) 10^{19} f/cm^3 ; dislocation density higher than 10^{12}cm^{-2}.

Fig. 4

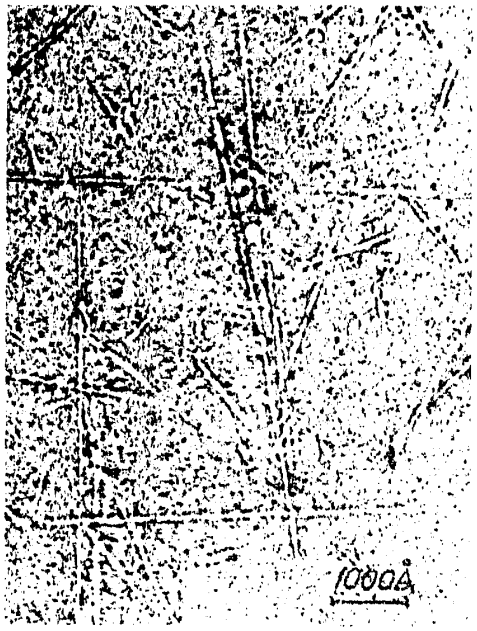

Fig. 5

Fig.4. Two-layer W-UO_2 object (90% of ^{235}U) after irradiation to 10^{18} f/cm^3.

Fig.5. Uranium dioxide specimen (0.7% of ^{235}U) irradiated to 9.10^{16} f/cm^3; dislocation density about 10^{11}cm^{-2}.

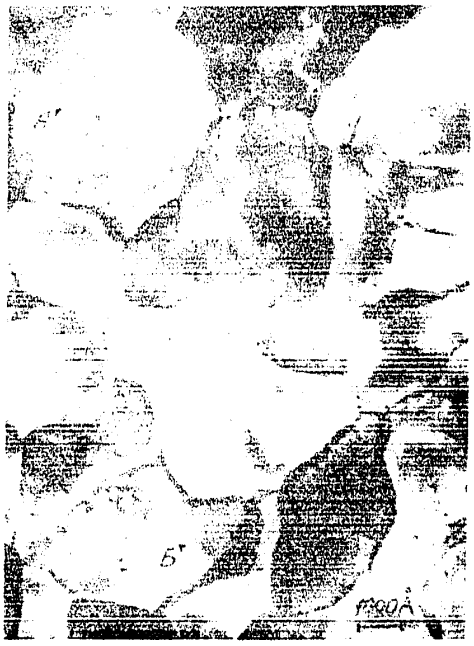

Fig.6. The same area of uranium dioxide specimen (0.11% of ^{235}U)
a) before irradiation
b) after irradiation to $1.4 \cdot 10^{16}$ f/cm^3;
А - А' , Б - Б'
- dislocations around stacking faults.

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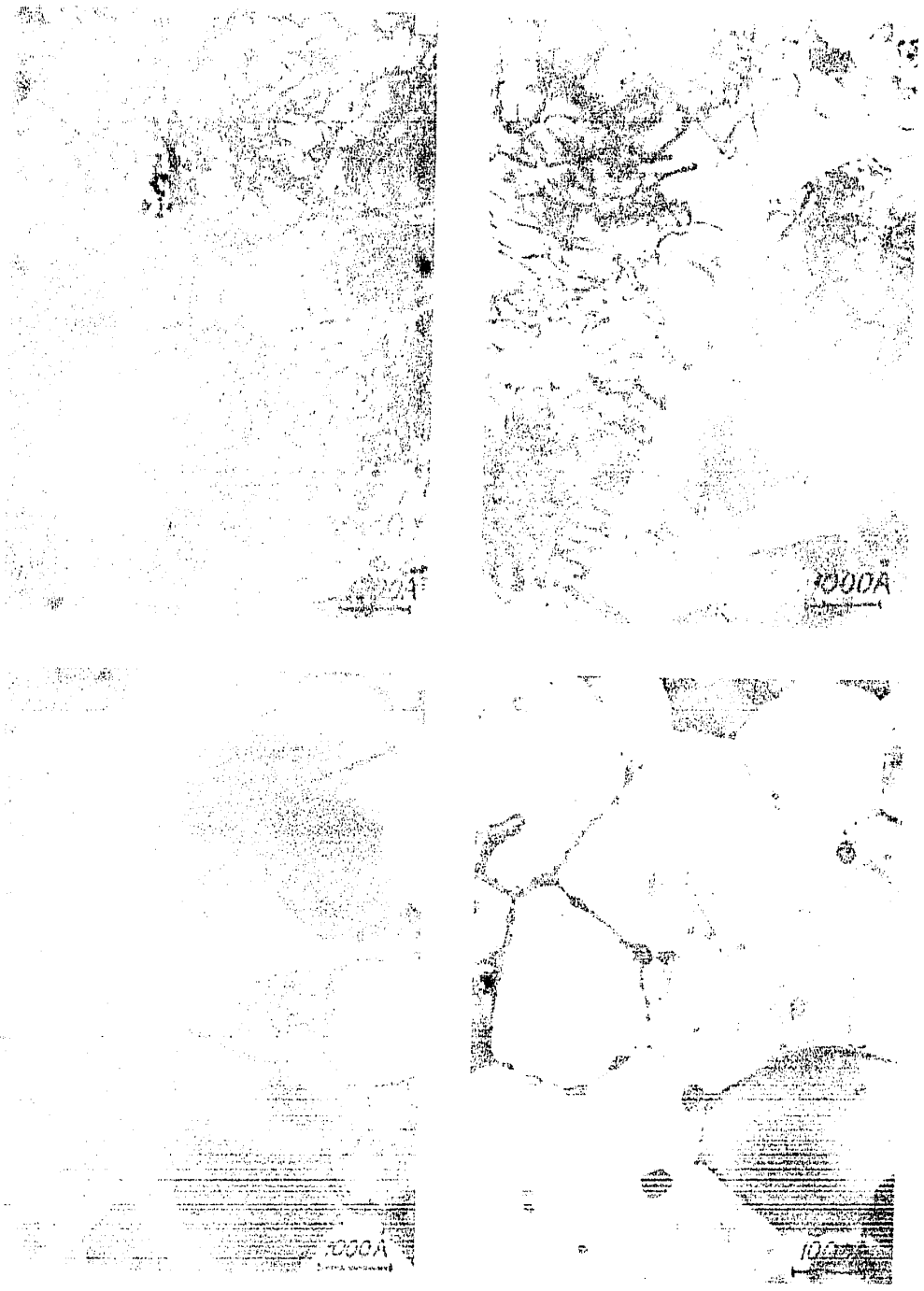

Fig.7. Irradiated uranium dioxide specimens (90% of ^{235}U) shown in Fig.3c.
a) after 10 min annealing at 900°C
b) after 10 min annealing at 1000°C
c) after 10 min annealing at 1100°C
d) after 10 min annealing at 1500°C

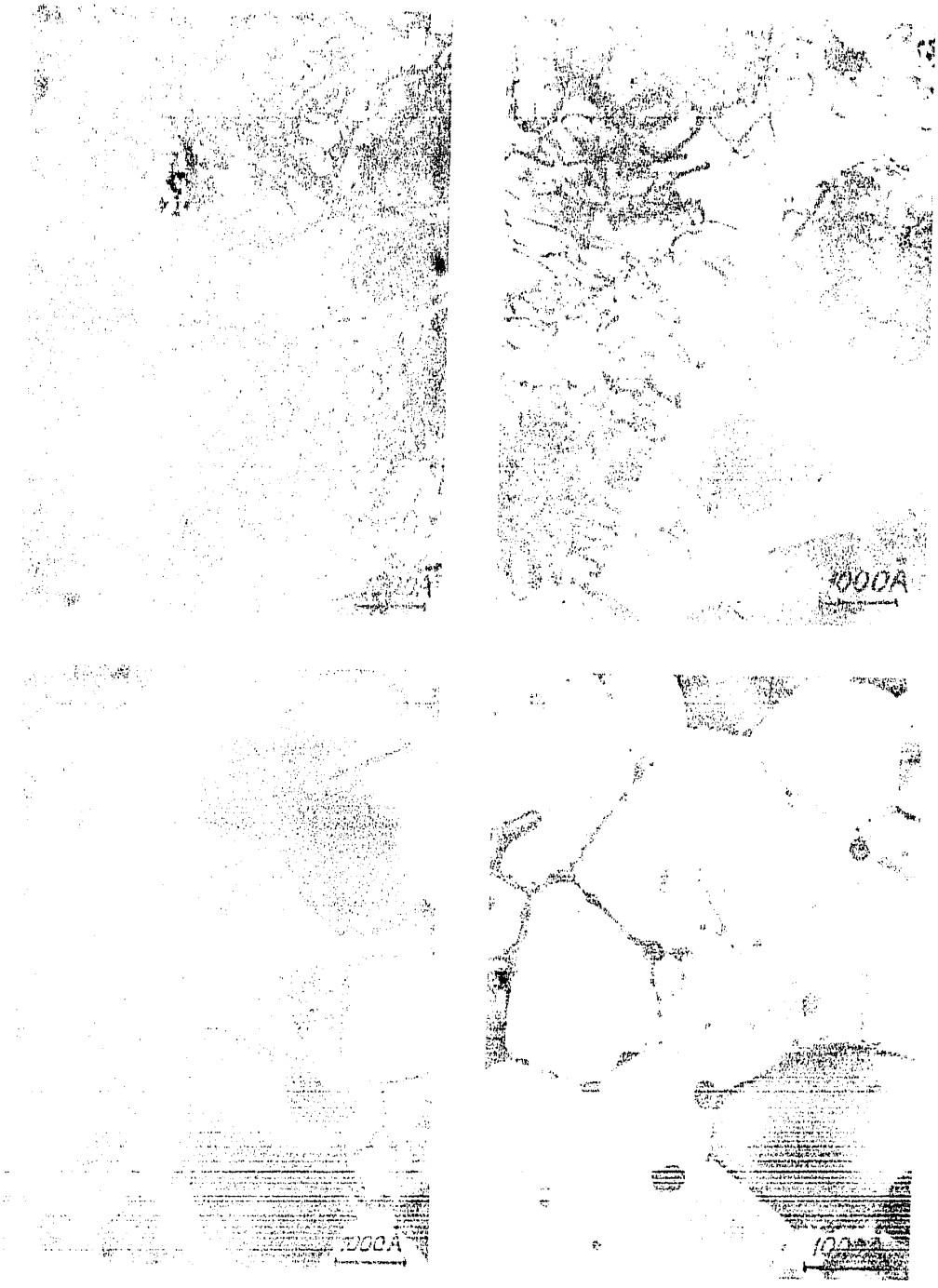

Fig.7. Irradiated uranium dioxide specimens (90% of ^{235}U) shown in Fig.3c.
a) after 10 min annealing at 900°C
b) after 10 min annealing at 1000°C
c) after 10 min annealing at 1100°C
d) after 10 min annealing at 1500°C